

ENVIRONMENTAL ASSESSMENT

An Eco-balance of a Recycling Plant for Spent Lead–Acid Batteries

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ABSTRACT / This study applies Life Cycle Assessment (LCA) methodology to present an *eco-balance* of a recycling plant that treats spent lead–acid batteries. The recycling plant uses pyrometallurgical treatment to obtain lead from spent batteries. The application of LCA methodology (ISO 14040 series) enabled us to assess the potential environ-

mental impacts arising from the recycling plant's operations. Thus, net emissions of greenhouse gases as well as other major environmental consequences were examined and hot spots inside the recycling plant were identified. A sensitivity analysis was also performed on certain variables to evaluate their effect on the LCA study. The LCA of a recycling plant for spent lead–acid batteries presented shows that this methodology allows all of the major environmental consequences associated with lead recycling using the pyrometallurgical process to be examined. The study highlights areas in which environmental improvements are easily achievable by a business, providing a basis for suggestions to minimize the environmental impact of its production phases, improving process and company performance in environmental terms.

Lead–acid batteries are complex industrial products made from a number of materials. They are used as starters for engines and can be divided into two general categories depending on their size and shape. The first are small batteries used in public and private transport (cars, buses, trucks, etc.) and the second group includes large batteries for industrial plants, particularly communications centers and electrical power stations. An average-size lead–acid battery (~14 kg of weight) is made from ~80% lead (grid, connections, battery paste), ~12% acid (aqueous solution of H_2SO_4), and ~8% plastics (box and other parts). It should be noted that battery compositions differ between a new lead battery and a spent one, as shown in Table 1 (Jolly and Rhin 1994; Zabaniotou and others 1999; COBAT 2003a; Daniel and others 2003; and measurements directly from the company studied in this article).

The difference in composition between a new and spent battery is due to the presence of “battery paste” (mainly salts and lead oxide) in a spent battery. This

material arises from the oxide-reduction process of the lead in a new battery and the reduction in concentration and amount of acid solution, as sulfuric acid combines with lead. Thus, the total lead contained in a spent battery comprises 45% in metal form (grids and connections) and 55% in the form of salts (PbSO_4 , $\text{PbO} \cdot \text{PbSO}_4$, PbO_2). The amounts of all the other materials are unaffected by the processes occurring inside the battery and, thus, their percentage content remain unchanged.

All of these materials have a high environmental impact if they are disposed of improperly. Currently, all of the materials they contain can be recovered and recycled, thereby conserving resources. Recycling lead–acid batteries not only includes production of recycled lead but also recycled plastic (in particular, polypropylene, polyethylene, and PVC) in addition to neutralizing the acid solution. Indeed, a recycled battery produces only 25% waste (20% dangerous waste and 5% plastics); thus, the collection and recycling of spent batteries enables the waste potentially produced from a discarded battery to be reduced by 75% by recycling lead and plastics and neutralizing acid, whereas a nonrecycled battery obviously produces 100% waste (COBAT 2000).

Not surprisingly, the process of recycling lead–acid batteries is one of great and growing interest to the world's lead industry. In 1990, about 85% of used bat-

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Table 1. Typical composition of a new average-size lead-acid battery and of an exhausted average-size lead-acid battery (about 14 kg)

Components of battery	New battery (%)	Spent battery (%)
Lead metal: grid and connections	28–30	28–30
Active paste: PbO	35–36	—
Battery paste: PbO ₂ , PbSO ₄ , PbO*PbSO ₄	—	48–50
Plastic: polypropylene, polyethylene, PVC	7–8	7–8
Acid solution: H ₂ O + H ₂ SO ₄	26–27	12–13
Other materials: paper, ebonite,	0.3–1	0.3–1

teries were recycled and about 47% of the total lead production worldwide came from secondary lead smelting (Jolly and Rhin 1994), and in 1996, roughly 96% of all battery lead was recycled (Battery Council International 2002).

Spent batteries are clearly classified as dangerous waste under Italian law (Italian Legislative Decree 22/97) in line with EC Directives. They are included in the European Catalogue of Waste (Attachment A) under the category “waste not otherwise specified in the catalogue” (code 16 00 00) (Micali and others 2001).

In Italy, the collection and recycling of spent lead–acid batteries is coordinated by an organization called COBAT [Consorzio Nazionale Obbligatorio batterie esauste e rifiuti piombosi (National Consortium for Spent Batteries and Leaded Waste)]. The organization, which was founded by the government in 1988, provides wide-ranging collection services (6 recycling plants, 86 collection networks, and more than 3000 disposal bins situated in numerous Italian cities) and also liaises with producers of this type of waste. In the year 2000, COBAT collected about 94% of all spent batteries, from which 96,000 tons of lead were obtained and 34 million liters of sulfuric acid were neutralized. Recycled lead represents 40% of the total production of lead in Italy and 37% of national demand for this metal (Anonymous 2001). The following data provide a general picture of the spent lead–acid battery collection activity in European countries during 2001: in Italy, COBAT collected about 96% (in 2002) of spent batteries; in Sweden, RETURBATT A.B. collected about 95%; in Austria UFT Startebatterien Gesmbh, collected about 90–95%; in Denmark, RETURBAT D.K. collected about 95%; in Norway, BATTERIRETUR collected about 95.4% (COBAT 2003b).

The most widely used technologies for recovery of lead are based on processes that require either the pyrometallurgical melting of leaded waste materials (Collivignarelli and others 1986; Pickles and Toguri 1993; Cole and others 1983; C.R.I. 1990; Marchese and others 1991) or processes that involve the electrochemical separation of lead (Micali and others 2001; Marchese and others 1991; Pickles and Toguri 1993; Lyons and Gillet 1977). The pyrometallurgical melting process is suitable for treating spent lead–acid batteries as well as other types of scrap lead, such as sheet lead, cable coatings, and so forth. This process can vary in relation to the type of oven used and the way in which the process is carried out; the latter can be either in two separate stages, first oxidation and then reduction, or in a single oxide-reduction stage (Pickles and Toguri 1993; Lyons and Gillet 1977). There can also be differences concerning other aspects of the process (i.e., the method of breaking up batteries, the recovery of byproducts, pollution prevention systems, etc.). Pyrometallurgical treatment of the battery paste is much simpler, uses less electricity than the electrochemical method, and has a lower environmental impact and, therefore, seems to be more advantageous (Pickles and Toguri 1993; Olper and Franchia 1988). According to COBAT, all of the existing lead recycling companies in Italy use the pyrometallurgical process (COBAT 2003a).

The above-reported data show that recycling lead–acid batteries makes a valuable contribution to the conservation of lead resources worldwide. Proper management of spent lead–acid batteries is also an issue of international importance due to the high environmental impact of all the materials they contain, and such impacts can be reduced by recycling plants, as demonstrated by the above-reported data. With these points in mind, we performed a Life Cycle Assessment (LCA) of a recycling plant for spent lead–acid batteries in order to explore the environmental aspects of this activity. More specifically, the aim of the study presented herein is to examine all of the major environmental consequences associated with lead recycling and to identify the hot spots of the product system being studied in order to obtain information that is useful for improving environmental management at the company level, which will then benefit the entire industrial sector. Hot spots are the stages of a product's life cycle in which environmental improvements can easily be achieved; thus, their identification enables alternative solutions to be proposed. By following the proposals, a business can minimize the environmental impact of production phases and improve processes and company performance.

Life Cycle Assessment Methodology

We have used the Life Cycle Assessment (LCA) method in our study. This method is used to analyze and assess the environmental loads and potential environmental impacts of a material, product, or service throughout its entire life cycle, from raw materials extraction and processing, through manufacturing, transport, use, and final disposal (ISO 14040 1997). The initial stage of this method requires that the product system to be studied be delimited from the surrounding environment by setting *system boundaries*, thereby defining the processes to be included in the study. A *functional unit* must also be defined as this forms the basis for calculations to be made (e.g., 1 tonne of the product studied).

Apart from the principles and framework of LCA set out in ISO 14040, the individual stages of an LCA study are set out in the following ISO standards for environmental management: ISO 14041: goal and scope definition and inventory analysis; ISO 14042: impact assessment; and ISO 14043: interpretation. These are briefly described here to illustrate the method we have adopted (ISO 14040 1997; ISO 14041 1998; ISO 14042 2000; ISO 14043 2000).

In the first step, *goal and scope definition*, the reason for carrying out the study is clearly defined, the product, process, or service system to be assessed is described, specifying the individual processes to be included in the study, and a functional unit for calculation is chosen. The processes included in the product system are then subjected to an *inventory analysis* in which inputs and outputs (energy, materials, and emissions) of each process are quantified and the data collected are related to one functional unit. The results of this step are then grouped into different impact categories in the *impact assessment*. This involves, first, classification according to the kind of environmental problem to which they contribute, followed by characterization in which contributions to all environmental impact categories are individually quantified and, finally, valuation, which compares the environmental categories to which each process contributes. The results are then subject to *interpretation* and this step translates them into opportunities to reduce the environmental impacts of the product system.

The LCA Case Study: An Eco-balance of a Recycling Plant for Spent Lead–Acid Batteries

Goal and Scope Definition

The goal of this study is to assess the potential environmental impacts arising from the recycling of

spent lead–acid batteries. In particular, the aim of the present study is to perform an *eco-balance* (Baldo 2000) of a recycling plant that obtains lead from spent lead–acid batteries via a pyrometallurgical process. The *eco-balance* provides a means to examine the net emissions of greenhouse gases, in addition to other major environmental consequences, and can also be used to identify the hot spots in the recycling plant, which are matched to the six phases of activity considered (production of ancillary materials, the three processing stages: crushing and neutralization, smelting and refining, plus transport and waste treatment).

Description of the System and Functional Unit. The system studied covers all of the recycling activities from the receipt of batteries by the business (including transport from collection networks and production of ancillary materials) to the output of lead and its delivery to battery manufacturers (including waste-management activities). System boundaries of this study are limited to Italy.

The recycling plant, where on-site data were collected (a more detailed description of data collection is given in the following subsection and Table 4), uses a pyrometallurgical process that can be split into three different production phases: crushing, smelting, and refining.

The first phase involves crushing and hydraulic separation, which separates out the main constituents of the batteries (plastics, lead, and acid), and these are treated as follows:

- Recyclable plastics (principally polypropylene, polyethylene, and PVC) are sent to other recycling plants and the plastic mix that cannot be recycled is sent to landfill.
- Battery paste and lead grids go on to the next processing phase (smelting).
- The acid solution is neutralized using slaked lime, the process giving off water and calcium sulfate. The water is used by the crushing process for separation of constituents and for cooling in the smelting process, and the calcium sulfate is sent for waste treatment.

The factory is organized so that all of the liquid effluents of the process are recycled in full; indeed, all water, from both the crushing area and the battery storage area, is collected in two tanks with an overall capacity of 900 mc. Periodically, the acid solution (H_2SO_4) is neutralized using slaked lime [$\text{Ca}(\text{OH})_2$], giving off water (H_2O) and calcium sulfate (CaSO_4). This water from the neutralization process [$\text{H}_2\text{SO}_4 + \text{Ca}(\text{OH})_2 \rightarrow \text{CaSO}_4 + 2 \text{H}_2\text{O}$] is normally used in

cooling/saturation of gases discharged from the oven. Rainwater collection facility means that only a minimal top-up is required, water being drawn from the municipal water supply. Therefore, the annual water balance is almost a closed cycle.

In the smelting process, battery paste and lead grids, together with the dusts recovered in the gas circuitry of the process, the ashes, and the slag generated in the refining process are smelted with the addition of a charge containing iron scraps, coke, and sodium carbonate. The oven is a rotary type and has a capacity of 15,000 L. Its working temperature is in the range 400–1000°C in the various operational phases and varies according to the quality of the load and the reagents, the type of fuel used, the combustion method, as well as the systems for cooling and treating gas discharges (in general, the lead grids melt at 400°C and are the first output, whereas the paste requires a temperature of at least 800°C). The end products of the smelting process are unrefined lead and smelting residues (De Angelis and others 2002). The latter are sent for waste treatment.

The unrefined lead from smelting then undergoes refining. In this process, it is usually integrated with “additives” to form alloys and then poured into ingot molds. This process produces refined lead and waste (refinery residues). The refined lead is of high purity (~99%) and can, therefore, be used directly by battery manufacturers; a small amount of refined lead (6–7%) is sent to other producers (e.g., to make keels for sailing boats). The waste produced is added to the smelting charge.

There are two separate systems for reduction of fumes: a plant for the smelting area and one for the refining area. Both systems involve the use of scrubbers and bag filters. The filters are systematically cleaned and the dust arising from cleaning filters is put back into the oven to recover any lead.

We also considered ancillary production, transport, and waste treatment phases in our environmental assessment of recycling activities. The ancillary materials production phase includes the production of all the materials necessary to carry out the recycling process, whereas the waste-treatment phase includes treatment of the waste produced by the recycling plant itself (plastics, smelting residues, sludge from the neutralization step). The transport phase includes all operations involved in the transportation of materials, discarded materials, and finished products coming into and going out of the factory. Potentially, these phases are important, as they could make a significant impact on the entire life cycle of recycled lead.

Figure 1 shows in detail the steps involved in lead production in the recycling plant. Figure 2 shows all of the processing steps relating to recycled lead and it also shows the system boundaries (steps in dotted boxes are not included in the system). All of the materials and energy flows needed for the recycling of lead are included in the system boundaries, as detailed in the next subsection.

The assessment and comparison of environmental impacts are based on the functional unit of one tonne of recycled lead delivered to the battery production site.

Data Quality, Assumptions, and Allocations. Specific data regarding the recycling process were obtained directly from a recycling plant and from other parties involved in this phase of production. The recycling plant is situated in Pace del Mela, an industrial area near Milazzo (Messina, Sicily, Italy). The firm had recently obtained ISO 14001 certification and management staff showed great interest in the study; this provides further assurance that data were collected carefully and thoroughly.

When on-site data were not available, they were obtained from the literature or from commercially available databases. The data collected refers only to the last 4 months of the year 2001, as a change of management occurred during that year which led to an increase in activity. Thus, the reference period chosen was limited to the period when production activity had stabilized at new levels. In this period, the recycling plant, working 7 days a week, had a total production capacity of between 44,500 and 46,800 tonnes of batteries per year.

System boundaries were defined to include all of the recycling activities of lead–acid batteries, including the production of ancillary materials, waste treatment, and the transport of materials to the recycling plant and transport from the recycling plant to the battery manufacturers (see Figure 2). Production of the recycling plant’s machinery and equipment fall outside the system boundaries.

We stress that data relating to the *crushing and neutralization process* could be underestimated for two reasons. The first is due to recycling of plastics. Polypropylene is sent to a different recycling plant that produces covers and cases for new batteries and another type of plastic is also partly recycled [a mix of polypropylene (PP), polyethylene (PE), polyesters, metals including copper, lead, etc., polyvinyl chloride (PVC) and ebonite] but relevant information was not provided by the business for reasons of confidentiality. The only estimate we were able to make was that an additional 1–2% PP can be recycled from this mix; therefore, we assumed that the remaining part was sent

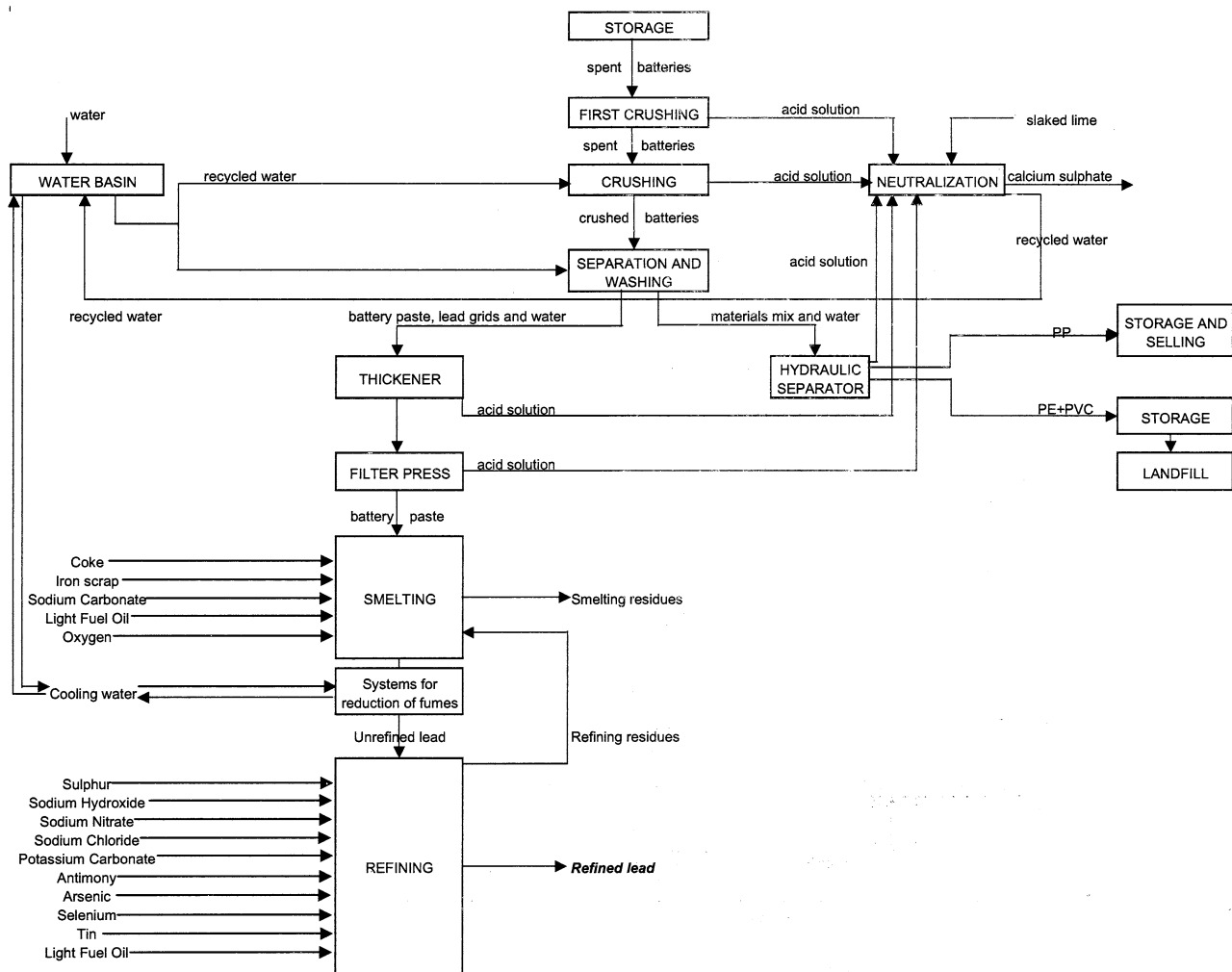


Figure 1. Recycling plant studied.

to a landfill. The latter is mainly PE because ebonite and PVC are no longer being used in plastics, as new materials (e.g., synthetic fabrics) are now available for use in battery manufacture (COBAT 2003a; Ahmed 1996). The second reason for data being underestimated relates to the sulfuric acid emissions (H_2SO_4 emissions), as it was impossible to collect data on these. It was therefore assumed that all of the acid solution was neutralized even though a small amount is lost through evaporation. However, the possibility of sulfuric acid emissions occurring was incorporated into the sensitivity analysis presented later (see Table 8 and Figures 4 and 5).

Background data include the following elements within the six phases considered:

- *Ancillary materials production phase.* Production of slaked lime [$\text{Ca}(\text{OH})_2$], scrap iron, sodium carbonate

(Na_2CO_3), coke (I-LCA database), oxygen (O_2), sulfur (S), sodium hydroxide (NaOH), sodium nitrate (NaNO_3), sodium chloride (NaCl), and tin (Sn)—all data from the DEAM database (Ecobilan 1999a) unless stated otherwise. Production of antimony (Sb), arsenic (As), potassium carbonate (K_2CO_3), and selenium (Se) were not included because it was not possible to collect the relevant data, either directly or from the database available.

- *Crushing phase.* Electricity production—data from the DEAM database (Ecobilan 1999a).
- *Smelting phase.* Electricity production and light fuel oil production and combustion—data from the DEAM database (Ecobilan 1999a).
- *Refining phase.* Electricity production and light fuel oil production and combustion—data from the DEAM database (Ecobilan 1999a).
- *Transport phase.* Site-specific data and DEAM data-

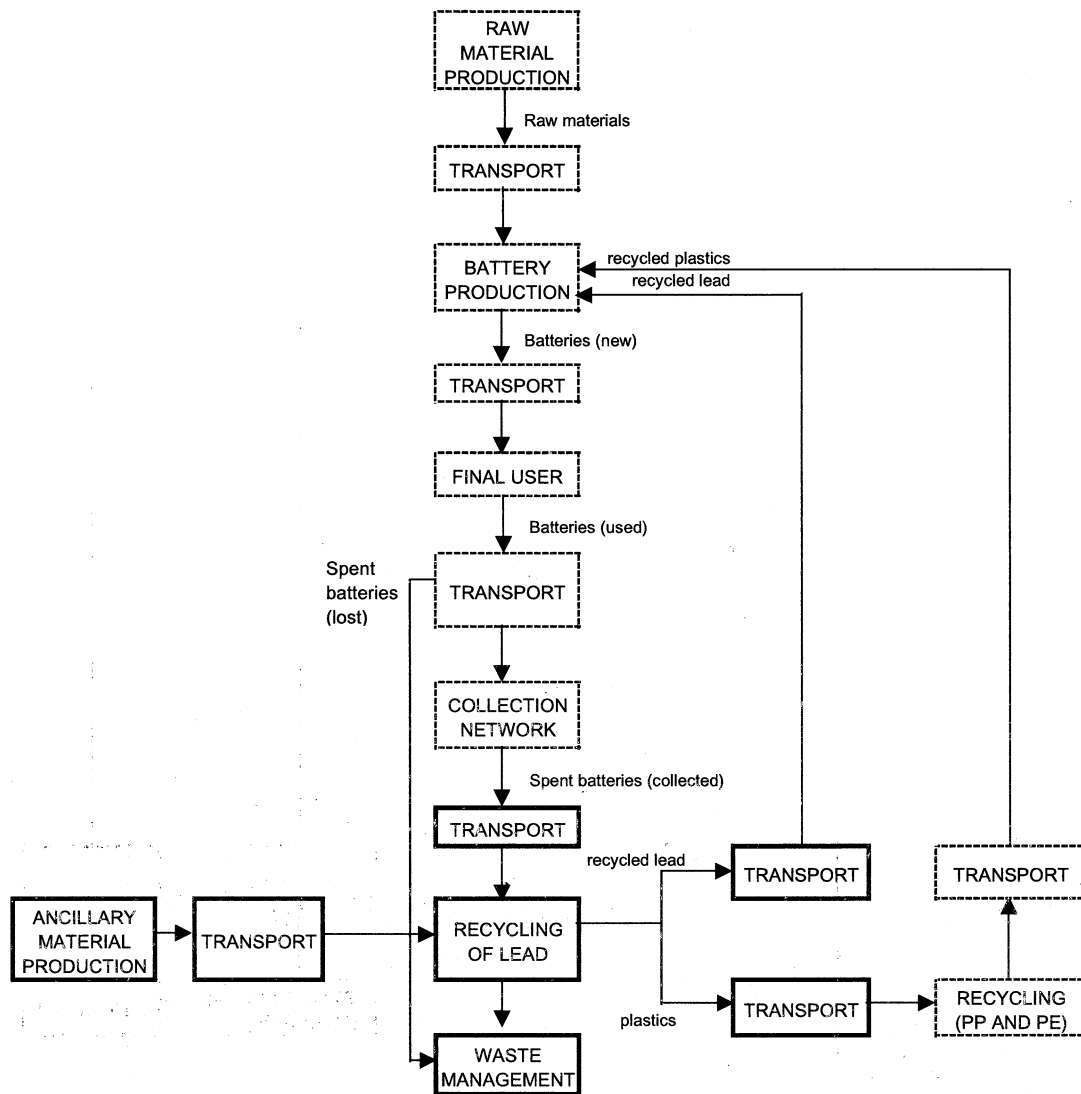


Figure 2. Lead–acid battery life cycle.

base (Ecobilan 1999a); includes the transportation of spent batteries from collecting points to the recycling plant, ancillary materials to the recycling plant, plastics to the plastic recycling plant, and refined lead from the recycling plant to battery manufacturers and wastes to a landfill or to other waste-management sites. Transportation linked to collection activities was not included because it was not possible to collect sufficient data.

- *Waste-treatment phase.* Avoided impact due to PP recycling and waste treatment of plastic mix: as described earlier plastics obtained in the crushing and neutralization process are partly recycled (mainly PP) and the remaining part is sent to a landfill (mainly PE). All data are from the DEAM database (Ecobilan

1999a). The avoided impact connected to PP recycling refers to the emissions from plastic production, which do not occur because PP is obtained from recycled material. Consequently, the avoided emissions are taken as credits in the total inventory of the system. In this phase, we also included the main pollutants in solid waste (sludge from the neutralization step and smelting residues) sent to other treatment sites.

Table 2 lists the metals content in calcium sulfate resulting from the neutralization process and metals in smelting residues; Table 3 presents the main air pollutants of the recycling plant.

The above assumptions should be taken into account when interpreting the results presented in this

Table 2. Metals in calcium sulfate resulting from crushing and neutralization process (process A) and metals in smelting residues resulting from smelting process (process B)

Metals	A (mg/kg)	B (mg/kg)
Copper	< 0.5	2
Arsenic	11	200
Cadmium	8.3	2
Chromium hexavalent	< 0.5	< 0.5
Mercury	< 0.1	< 0.1
Lead	390	47000
Selenium	—	< 0.1

Note: Data supplied by the company.

Table 3. Main air pollutants of the recycling plant (g/kg of refined lead)

Air pollutants	g/kg
Fugitive H ₂ SO ₄ emission	Not determinable
Fugitive Pb emission	Not determinable
Pb	0.027
Particulates	0.48
Nitrogen oxides (NO _x)	2.15
Sulfur dioxide (SO ₂)	4.2
Carbon monoxide (CO)	0.005
Carbon dioxide (CO ₂)	604.5

Note: Calculated from data supplied by the company and COBAT data.

study. In line with ISO 14041, allocation of data was avoided, done by choosing refined lead as the functional unit without distinguishing among its various alloys.

All of the data sources used in this study are specified in more detail in Table 4.

Inventory Analysis and Impact Assessment Methods

Data collection and inventory analysis were carried out in accordance with ISO 14040 and ISO 14041 standards. The software used was Tools for Environmental Analysis and Management TEAMTM Version 3.0 (Ecobilan 1999b). The data are either site-specific data collected from the recycling plant described earlier or were obtained from the DEAMTM database (Ecobilan 1999a) and the I-LCA database (ANPA 2000).

Table 5 shows the results of inventory analysis where only the main inputs and outputs of the system studied are included. The table does not include material flows inside the recycling plant, namely the residues from refining that are added to the oven charge (49.81 kg per functional unit) nor the water produced from the neutralization of the aqueous sulfuric acid (347.61 L

per functional unit). This water, topped off with rain-water and water from the municipal supply network, is used for cooling/saturation of waste gas from the oven.

Also not included are any fugitive emissions of H₂SO₄ and Pb into the atmosphere. This, to reiterate this point, is because it was impossible to collect data on these and, in any case, their modest amounts would contribute so little to the various impact categories analyzed that they are irrelevant. However, the sensitivity analysis includes a number of hypotheses related to these emissions.

We investigated nine different impact categories (Ecobilan 1999b; Heijungs and others 1992; Baldo 2000; Houghton and others 1991; SETAC 1993; WMO 1989; WMO 1994) for the purpose of environmental assessment (Table 6). Although one of these categories relates to odor (a very strong odor can be detected on the production site and it is, thus, considered a very important factor), we stress that this category should be treated with caution because it was not possible to collect data regarding widespread emissions of H₂SO₄. Ecopoints were used to provide a general weighting factor for the sensitivity analysis. An ecopoint is a measure of the overall environmental impact of a particular product or process covering various environmental impacts (climate change, fossil fuel depletion, ozone depletion, human toxicity, waste disposal, acid deposition, eutrophication, etc.) obtained by adding together the score for each issue, calculated by multiplying the normalized impact with its percentage weighting (Braunschweig and Müller-Wenk 1993; Baldo 2000; Ecobilan 1999b).

Impact Assessment and Interpretation

Figure 3 shows the individual contributions made by the six process stages to each impact category expressed as percentages, where the 100% total contributions to each impact category ignores negative contributions and avoided emissions (the latter relate mainly to the avoided impacts linked to PP recycling and the neutralization of acid solution). From the figure, it can be seen that the smelting stage contributes the most to all of the impact categories (greater than 65% in every case, except for terrestrial ecotoxicity), followed by the refining stage (contribution exceeding 28% in all categories, except terrestrial ecotoxicity). The waste-treatment phase essentially accounts for all of the terrestrial ecotoxicity (more than 99%), whereas its contributions to other impact categories are minimal or zero. The transport stage makes only limited contributions to each category and the contributions of the crushing and neutralization stage are almost negligible.

Table 4. Data sources

Process type	Data sources
Electricity production	DEAM Database, production in Italy (1996)
Crushing and separation of battery components	Site-specific data (measurements referred to 2001)
Slaked lime production	DEAM Database
Neutralization of acid solution	Site specific data (measurements and estimates referred to 2001)
Scrap iron production	DEAM Database
Sodium carbonate production	DEAM Database
Coke production	I-LCA database
Oxygen production	DEAM Database
Light fuel oil production and combustion	DEAM Database
Smelting of lead scraps	Site-specific data (measurements referred to 2001)
Air control system and air emissions	Site-specific data (measurements and estimates referred to 2001), COBAT 2000, COBAT 2003a, COBAT 2003b
Water cycle system	Site-specific data (estimates referred to 2001)
Lead recovery system (internal and external)	Site-specific data (measurements and estimates 1 referred to 2001)
Sulfur production	DEAM Database
Sodium hydroxide production	DEAM Database
Sodium nitrate production	DEAM Database
Sodium chloride production	DEAM Database
Tin production	DEAM Database
Refining of unrefined lead	Site-specific data (measurements referred to 2001)
Road transport	DEAM Database – combustion of diesel oil in trucks (maximum load of 1 6 tons and of 28 tons)
Sea transport	DEAM Database - combustion of heavy fuel oil for transport by sea tanker
Transportation of spent batteries	Site-specific data (measurements referred to 2001)
Transportation of ancillary materials	Site-specific data (measurements referred to 2001)
Transportation of recyclable materials	Site-specific data (measurements referred to 2001)
Transportation of waste	Site-specific data (measurements referred to 2001)

The impact categories affected by each process stage and the main emissions contributing thereto are set out in Table 7 (avoided emissions are not included in the table). For each impact category considered, only the pollutant responsible for the most significant contribution is reported. The percentages given refer to the total result of a given impact category and only contributions exceeding 3% are reported.

The results of the contributions analysis show that the ancillary production phase and the crushing and neutralization stage make insignificant contributions to impact categories, and they have, therefore, not been included in Table 7 (their contribution is nil or lower than 3%). However, it is important to point out that the crushing and neutralization step is probably underestimated, at least as far as odor and air acidification are concerned, essentially because of the lack of data relating to Pb and sulfuric acid dispersion (Pb and H₂SO₄ fugitive emissions). The transport stage is an important process but it is certainly underestimated for the time being. We believe that the missing data relating to collection networks to be essential to obtain a reliable scenario of recycling activity.

The smelting phase, followed by the refining one, are the ones associated with the greatest environmental problems, mainly with the emissions of SO₂, CO₂, and NO_x and it is evident that Pb emissions make no significant contribution to any of the categories considered. This is because the plant is fitted with effective systems for total recycling of all liquid effluent of the process and for reduction of fumes, designed to minimize the Pb emissions into groundwater and into the atmosphere.

The waste-treatment phase is the only point at which significant Pb emissions, into the soil, were found; the waste that leaves the plant to go for treatment at other sites does contain significant amounts of lead (see Table 2). Information regarding this waste, comprising sludge from neutralization treatment and smelting residues, could not be obtained from the other plants for reasons of privacy.

A sensitivity analysis was conducted to examine the effects when varying the base case data of some parameters. These parameters and their changes were chosen considering realistic and practical alternative scenarios considering the technical structure of the

Table 5. Main inputs and outputs of the system per functional unit

Input	Units	Amount	Output	Units	Amount
Spent batteries	kg	3499.97	Refined lead	kg	1000
Ancillary materials			Air emission		
Antimony	kg	19.01	Carbon dioxide (CO ₂)	g	555,114
Arsenic	kg	1.66	Carbon monoxide (CO)	g	4.59
Coke	kg	79.44	Lead (Pb)	g	24.61
Scrap iron	kg	280.54	Nitrogen oxides (NO _x)	g	2002.09
Slaked lime	kg	46.74	Particulates	g	450.81
Oxygen	kg	129.61	Sulfur dioxide (SO ₂)	g	3820.69
Potassium carbonate	kg	0.43	Solid waste		
Selenium	kg	0.04	Plastic mix to recycling	kg	176.82
Sodium carbonate	kg	19.59	Plastic mix to landfill	kg	136.78
Sodium chloride	kg	0.39	Sludge from neutralization	kg	81.17
Sodium hydroxide	kg	6.03	Including:		
Sodium nitrate	kg	2.49	Arsenic 0.89 g		
Sulfur	kg	0.95	Cadmium 0.67 g		
Tin	kg	0.56	Chromium 0.04 g		
Energy consumption			Copper 0.04 g		
Electricity	MJ elec	1165.08	Lead 31.66 g		
Light fuel oil	kg	110.86	Mercury 0.01 g		
Water consumption			Smelting residues	kg	422.21
Water (Public Network)	L	92.11	Including:		
			Arsenic 84.44 g		
			Cadmium 0.84 g		
			Chromium 0.21 g		
			Copper 0.84 g		
			Lead 19,844 g		
			Mercury 0.04 g		
			Selenium 0.04 g		

recycling plant under examination; these changes are presented in Table 8.

Each parameter was changed independent of all the others so that the extent of its effects on the base case could be assessed on its own. Accordingly, no single sensitivity case represents the best or worst situation under which these systems might operate.

Each modification to the parameters considered brings about a series of changes to the system under study, detailed as follows:

- Case 1: Fuel used in the smelting and in the refining step. The production and combustion of light fuel oil (LFO) was substituted with the production and combustion of natural gas (low NO_x).
- Case 2: Materials recycled. The possibility of recycling the PE contained in the plastic mix is considered which in the base case was sent to a landfill. In this scenario, the avoided impact connected with PE production is considered, but the analysis does not include the recycling of PE.
- Case 3: Treatment of aqueous solution of H₂SO₄. Instead of neutralizing the aqueous solution of H₂SO₄, the possibility of selling it was considered. This

scenario would lead to a series of changes to the system analyzed in the base case as follows: elimination from the system of the slaked lime production and the entire neutralization phase; reduction of solid wastes (sludge resulting from neutralization step); the addition of liquid effluents and related water emissions; inclusion of the avoided impact connected with H₂SO₄ production; and higher water consumption in the crushing step and in the fume cooling phase, due to the lack of water production in the neutralization step. In the transport phase, the part relating to carriage of slaked lime was removed; the transport of sludge from neutralization step was not eliminated, as it was considered more or less equivalent to the transportation of H₂SO₄ to battery production sites.

- Case 4: Energy consumption in the smelting step. The effects arising from the possibility of reducing energy consumption (electricity and light fuel oil) in the smelting phase by 25% was considered. The transport phase considered lower amounts of light fuel oil to be carried.
- Case 5: Energy consumption in the refining step. The effects arising from the possibility of reducing energy consumption (electricity and light fuel oil) in

Table 6. Impact categories

Impact categories	Method	Unit
Air acidification	University of Leiden, Centre of Environmental Science (CML)	g eq. hydrogen (H^+)
Aquatic ecotoxicity	University of Leiden, Centre of Environmental Science (CML)	$1e^3 m^3$
Depletion of ozone layer	World Meteorological Organization (WMO)	g eq. trichlorofluoromethane (CFC-11)
Eutrophication (water)	University of Leiden, Centre of Environmental Science (CML)	g eq. phosphates (PO_4^{3-})
Greenhouse effect (direct, 100 y)	Intergovernmental Panel on Climate (IPPC)	g eq. carbon dioxide (CO_2)
Human toxicity	University of Leiden, Centre of Environmental Science (CML)	g
Odor (air)	University of Leiden, Centre of Environmental Science (CML)	m^3
Photochemical oxidant formation	World Meteorological Organization (WMO)	g eq. ethylene
Terrestrial ecotoxicity	University of Leiden, Centre of Environmental Science (CML)	t

Table 7. Impact categories and main pollutants contributing thereto

Process	Impact categories	%	Mainly caused by	%
Smelting	Eutrophication (water)	69.13	Nitrogenous matter	39.33
	Odor (air)	68.82	Hydrogen sulfide	47.54
	Greenhouse effect	68.62	Carbon dioxide	65.48
	Depletion of the ozone layer	68.61	Halon 1301	68.61
	Photochemical oxidant formation	68.18	Hydrocarbons (except methane)	61.10
	Human toxicity	66.58	Sulfur oxides	39.92
	Aquatic ecotoxicity	66.47	Cadmium	48.87
	Air acidification	66.02	Sulfur oxides	46.82
Refining	Eutrophication (water)	30.04	Nitrogenous matter	17.09
	Odor (air)	29.91	Hydrogen sulfide	20.66
	Depletion of the ozone layer	29.82	Halon 1301	29.82
	Greenhouse effect	29.82	Carbon dioxide	28.45
	Photochemical oxidant formation	29.63	Hydrocarbons (except methane)	26.55
	Human toxicity	28.91	Sulfur oxides	17.33
	Aquatic ecotoxicity	28.88	Cadmium	21.24
	Air acidification	28.67	Sulfur oxides	20.33
Transport	Air acidification	5.71	Nitrogen oxides	5.11
	Human toxicity	4.75	Nitrogen oxides	4.07
	Photochemical oxidant formation	2.51	Hydrocarbons (except methane)	2.37
	Terrestrial ecotoxicity	99.98	Lead	96.31
Waste treatment	Aquatic ecotoxicity	3.09	Cadmium	3.11

Notes: Percentages refer to the total result of a given impact category.

the refining phase by 50% was considered. The transport phase considered lower amounts of light fuel oil to be carried.

- Case 6: Improvement of gas control and treatment for SO_2 emission reduction. The effects arising from the possibility of reducing SO_2 emissions by 50% was considered. In the absence of the technical means by which such reductions could be achieved, no other change was made to the system analyzed. In spite of this, the 50% reduction of SO_2
- Case 7: Recovery of Pb from smelting residues. The possibility of recovering an additional 80% of the Pb still present in smelting residues (see Table 2) was considered. This scenario led to the following changes to the system analyzed: an increase in the amount of refined lead obtained from the process; a decrease in the amount of Pb contained in solid

emissions did not significantly affect overall the potential environmental impacts to which these emissions are linked.

Table 8. Variables changed in sensitivity analysis

N	Variable	Base case	Assumptions changed
1	Fuel used in the smelting and in the refining steps	Light Fuel Oil	Natural gas (low NO _x)
2	Materials recycled	Plastic mix (principally PE) is sent to landfill	PE contained in the plastic mix is recycled (recycling activity is not included in the inventory, and the avoided impact connected to the production of PE is included)
3	Treatment of aqueous solution of H ₂ SO ₄	Neutralization with slaked lime	Sales of H ₂ SO ₄
4	Energy consumption in the smelting step	100%	75%
5	Energy consumption in the refining step	100%	50%
6	Improvement of gas control and treatment for SO ₂ emission reduction	100%	50%
7	Recovery of Pb from smelting residues	0%	80%
8	Fugitive emissions of H ₂ SO ₄ in crushing step	0%	(a) 5% (b) 10%
9	Fugitive emissions of Pb in crushing step	0%	(a) 5% (b) 10%

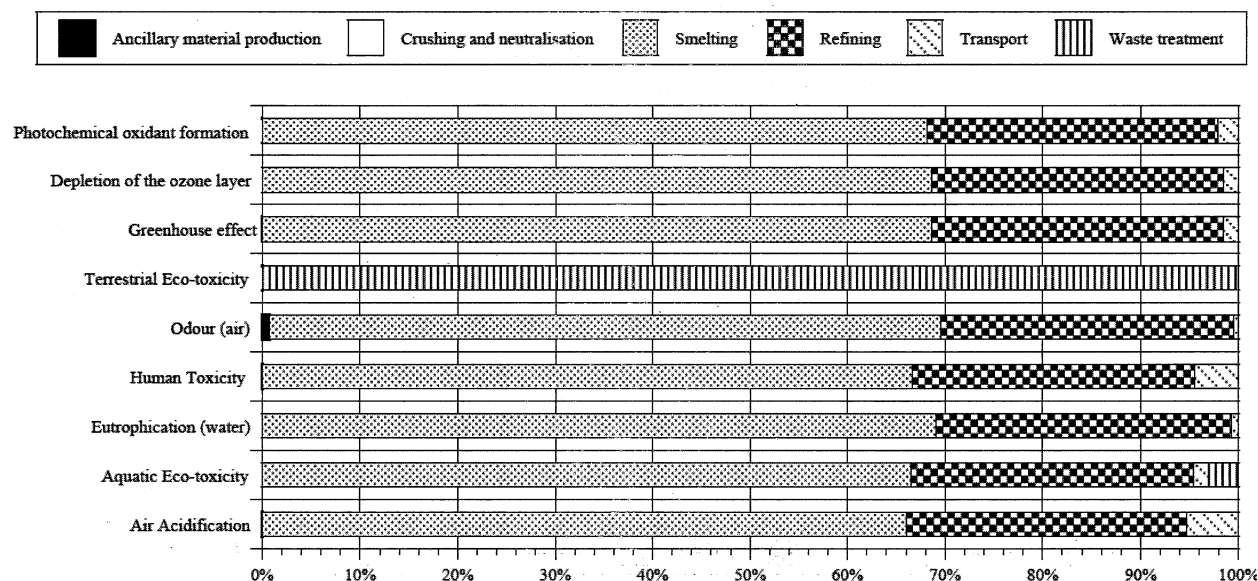


Figure 3. Impact categories studied.

waste (smelting residues); a reduction in weight of smelting residues.

- Case 8: Fugitive emissions of H₂SO₄ in crushing step. The effects of fugitive H₂SO₄ emissions in the crushing step were evaluated: setting them at 5% (case 8a) or 10% (case 8b) of the acid content of the aqueous solution (about 20% w/w of H₂SO₄) in the spent batteries coming into the plant.
- Case 9: Fugitive emissions of Pb in crushing step. The effects arising from fugitive emissions Pb in the crushing step was assessed, setting them at 5% (case 9a) or 10% (case 9b) of the lead salts and oxides contained in the spent batteries entering the plant.

Figure 4 shows the results of the sensitivity analysis using a general weighting factor based on ecopoints for each processing stage considered. Separate charts are produced for energy and waste, air emissions, and water emissions from which it can be seen that air emissions are the most relevant.

An overview of the sensitivity analysis reveals that the use of natural gas instead of light fuel oil has the greatest effect on the system analyzed. Greater energy efficiency in the refining step would also improve the eco-balance of the system, whereas the other assumptions have no noticeable effect with reference to the base case.

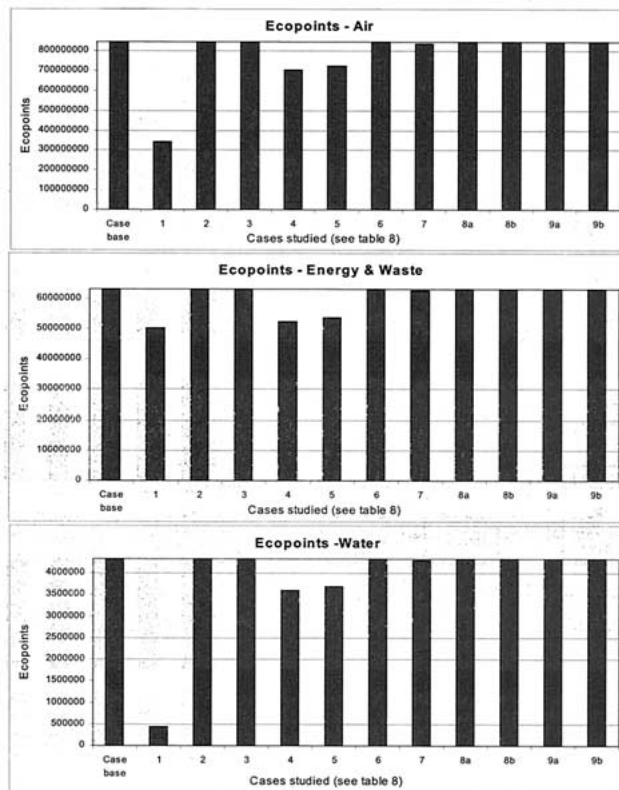


Figure 4. Sensitivity results for ecopoints.

However, additional elements of analysis can be highlighted if a further sensitivity analysis is performed on some of the individual impact categories reported in Table 6 for the variables described above. Figure 5 compares the results of the sensitivity analysis regarding air acidification, eutrophication, human toxicity, terrestrial ecotoxicity, and greenhouse effect. The base case is set at 0 and the percentage gains and losses on this are presented for each of the other scenarios considered in the sensitivity analysis (see Table 8).

Figure 5 clearly shows that scenario 1—natural gas used in the smelting and in the refining step in place of LFO—is the one that, compared to the base case (line 0), brings about the most significant improvements in the impact categories taken into consideration (air acidification, -65% ; eutrophication, -97% ; human toxicity, -65% ; greenhouse effect, -37%), with the exception of terrestrial ecotoxicity ($+9\%$). There are also potential improvements linked to scenario 4—energy savings in smelting step—and scenario 5—energy savings in refining step—as follows: air acidification, -16% and -14% , eutrophication, -17% and -15% ; human toxicity, -17% and -14% ; terrestrial

ecotoxicity, -0.3% in both cases; greenhouse effect, -17% and -15% . In scenario 7—recovery of Pb from smelting residues—a difference of -77% compared to the base case in the impact category terrestrial ecotoxicity would be obtained, whereas there are only modest improvements ($\sim -1\%$) in the other impact categories. The scenarios regarding fugitive emissions of Pb into the air show a worsening of the situation, limited however to the impact category terrestrial ecotoxicity, compared to the base case of $+85\%$ for scenario 9a (5%) and $+170\%$ for scenario 9b (10%). In contrast, the analogous scenarios of fugitive H_2SO_4 emissions (scenarios 8a and 8b) would make no greater contributions to the impact categories analyzed. In all of the other scenarios, the percentage variation (+/-) of impact categories are minimal or zero.

Conclusions

The disposal of spent lead-acid batteries is an increasingly important environmental problem of international concern. Two fundamental environmental issues are involved: protection, due to the high environmental impact of all the materials these batteries contain, and conservation of resources (in this case, lead).

The LCA of a recycling plant for spent lead-acid batteries presented herein shows that this method allows all of the major environmental consequences associated with lead recycling using the pyrometallurgical process to be examined. The knowledge acquired from the study will make the recycling company more aware in their environmental management and the information provided could be useful for improving environmental management not only at company level but also the whole Italian industrial sector, considering that all of the Italian recycling companies use the pyrometallurgical process.

The hot spots in the various stages of the life cycle of a product revealed by this LCA study highlight areas in which environmental improvements are easily achievable by a business providing a basis for suggestions to minimize the environmental impact of its production phases, improving process and company performance in environmental terms. Considering that the smelting stage contributes the most to all impact categories, followed by refining, improvement options should be concentrated within these steps, mainly in terms of energy improvements and savings. Also, the possibility of additional recovery of lead from refining residues would bring about an improvement in environmental

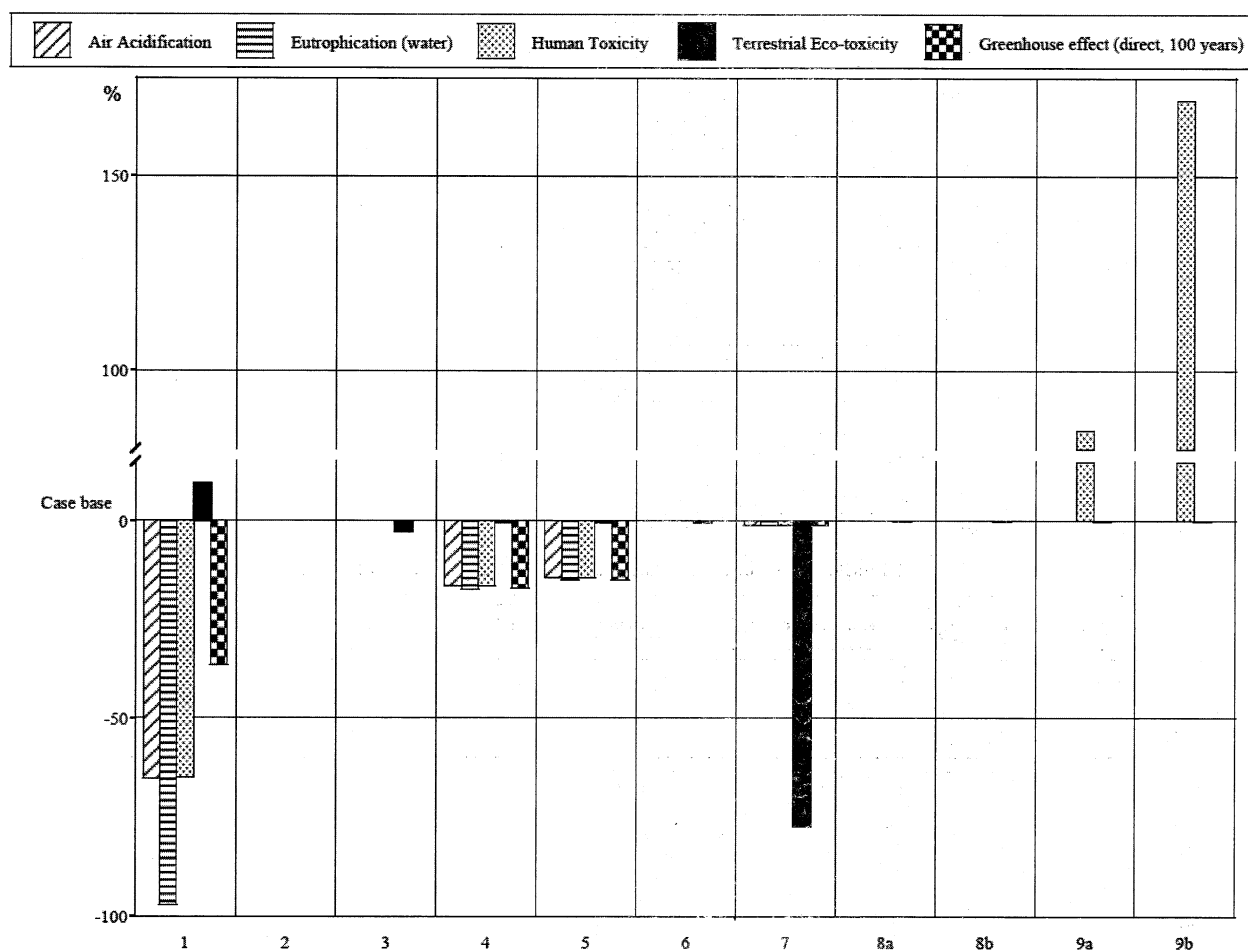


Figure 5. Sensitivity results for impact categories.

terms, but such a possibility should be carefully evaluated in association with an analysis of economic feasibility. The sulfuric acid releases and emissions (which often represent the type of emission that most concerns the community close to the plant) do not seem to cause significant environmental problems and, therefore, in contrast with public opinion, these do not constitute a hot spot for the plant, as it deals with these adequately.

A variety of alternatives were considered in the sensitivity analysis, the results of which provide considerations and options that company management can use to evaluate opportunities for improvement.

Although the results from this study were based on data concerning a single Italian recycling plant, the basic findings could be exploited by other companies operating in this industrial sector that use the pyrometallurgical process.

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